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TITLE: DESIGNS OF PULSED POWER CRYOGENIC TRANSFORMERS

AUTHOR(S): S. K. Singh, C. J. Heyne, D. T. Hackworth, E. J. Shestak, and P. W. Eckels -- Westinghouse R&D Center Pittsburgh, PA

J. D. Rogers, CTR-4, Los Alamos National Laboratory

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DESIGNS OF PULSED POWER CRYOGENIC TRANSFORMERS*

S. K. Singh, C. J. Heyne, D. T. Hackworth, E. J. Shestak, P. W. Eckels
Westinghouse R&D Center
Pittsburgh, PA

and

J. D. Rogers
Los Alamos National Laboratory
Los Alamos, NM

ABSTRACT

The Westinghouse Electric Corporation has completed designs of three pulsed power cryogenic transformers for the Los Alamos National Laboratory. These transformers will be configured to transfer their stored energy sequentially to an electromagnetic launcher and form a three-stage power supply. The pulse transformers will act as two winding energy storage solenoids which provide a high current and energy pulse compression by transforming a 50 kA power supply into a megamp level power supply more appropriate for the electromagnetic launcher duty. This system differs from more traditional transformer applications in that significant current levels do not exist simultaneously in the two windings of the pulse transformer. This paper describes the designs of the pulsed power cryogenic transformers.

INTRODUCTION

The configuration of the launcher system determines the direction and magnitude of the current flow within the transformer windings and therefore affects the magnitude and directions of coil forces. The electromagnetic launcher system configuration is a multi-staged variant of the single stage system shown in Figure 1. The pulse transformers will act as two winding energy storage solenoids which provide energy pulse compression while transforming a high voltage, low current power supply into a lower voltage, higher current supply more appropriate for the electromagnetic launcher duty. The three transformers will be configured to transfer their stored energy sequentially to the rail gun and form a three-stage power supply with each stage of the supply essentially equivalent to the system shown in Figure 1. This system differs from more traditional transformer applications in that significant current levels do not simultaneously exist in the two windings of the pulse transformers. Therefore, all forces act in the outward radial direction and a mechanical design based on the containment of outward radial forces and maintaining axial coil compression is appropriate.

DESIGN CONCEPT

The design parameters are given in Table 1.[1] The transformer designs make maximum use of proven design and manufacturing technology which results in a rugged, highly reliable transformer system for the electromagnetic launcher. The design concept is two-layer, air core, solenoid type pulse transformers. Cooling will be accomplished through pool boiling in liquid nitrogen bath, with heat transfer surfaces sized to accommodate the required repetition rate.

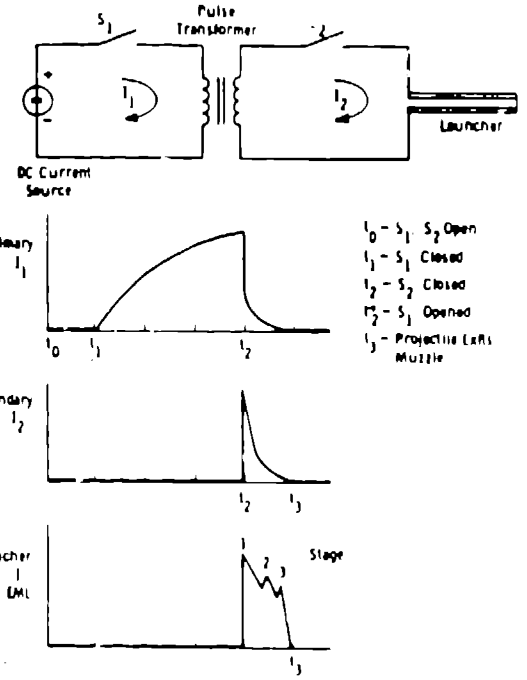

Figure 1 — EML system configuration for a single stage of a 3-stage power supply.

Coil geometries are designed to prevent excessive temperature rise and thermal stresses resulting from the proposed duty cycle.

The transformer secondary winding is produced by machining stepped slots through an appropriately sized copper cylinder for Transformer 1 and flat bending insulated conductor for Transformers 2 and 3. Turn insulation on the secondary windings is provided by the separation distance in the liquid nitrogen for the machined coil and Kapton wrap for the wound secondaries. Distance between secondary turns of Transformer 1 will be maintained with G10 spacers which supply compressive strength in the axial direction of the transformer secondary winding. Axial and cylindrical support of the secondary will be provided by interlocking axial bars and circular plates which are rigidly attached to the secondary winding.

The outer circumference of the transformer secondary windings, whether machined or flat wound, are wrapped with overlapping layers of Kapton film to form the insulation layer between the 200 kV primary and the 10 kV secondary winding for transformer 1 and 140 kV primary and the 10 kV secondary for transformers 2 and 3. An application of epoxy-impregnated glass cloth is applied over the Kapton layers to protect the insulation from possible puncture or damage during assembly of the transformer

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Table 1

Transformer Parameters

	Transformer No. 1	Transformer Nos. 2 & 3
Primary Winding		
Height, cm	213	152
Radius average, cm	125	75
Number turns	120	109
Peak current, kA	50	50
Peak voltage across coil, kV	200	140
Peak voltage between primary and secondary, kV	110	80
Charge time, s	3	3
Energy storage, MJ	33.5	14.4
Inductance, mH	26.5	11.5
Secondary Winding		
Height, cm	213	152
Radius average, cm	119.13	69.23
Gap between primary and secondary, cm	1.0	1.0
Number turns	6	16
Peak current, MA	0.950	0.314
Peak voltage across coil, kV	10	10
Inductance, mH	0.062	0.222
Coupling coefficient between primary and secondary	0.95	0.923
Mutual inductance between primary and secondary, mH	1.22	1.43
Conductor		
Primary winding edge wound, cm (OFHC copper)	1.71X7.2	1.33X7.0
Secondary winding, cm	2.54 thick	2.54 thick

primary winding and to provide a machinable surface for mounting the primary winding.

The primary windings of the transformers are produced by edge bending appropriately sized OFHC copper conductor. The primary winding conductor segments are joined using brazed joints to form a continuous conductor. The edge bent conductor is insulated with a Kapton and Nomex wrap and then a layer of epoxy loaded glass tape is applied to protect the insulation. The primaries are lined with a bore liner consisting of epoxy glass cloth. The bore liner is provided to allow machining of the primary bores to the appropriate tolerances. The primary winding, after bore machining, will be heated to increase its diameter and then placed over the prepared secondary winding to achieve a shrink fit. This will ensure mechanical integrity during all portions of the duty cycle. Final assembly which provides axial support and compression to the wound transformer will then be completed. The design concept for Transformer No. 1 is shown in Figure 2. The concept for Transformers 2 and 3 is similar except the secondaries use flat wound conductors.

INSULATION SYSTEM

The primary conductor insulation is a Kapton tape based system with a Nomex and then an epoxy loaded glass tape overwrap for protection and coil bonding.

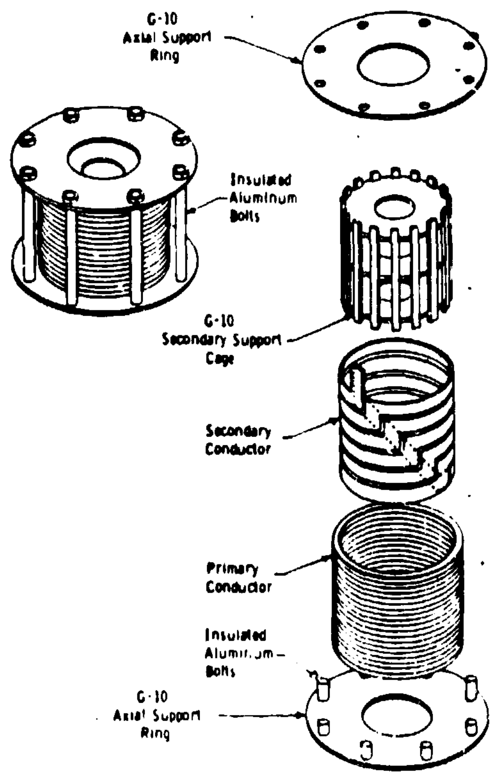

Figure 2 — Design concept for Transformer No. 1.

The insulation between the primary and secondary windings consists of a multi-wrap of Kapton sheets covered with an epoxy glass build-up for protection and to provide a machinable surface for shrink fit of the primary winding. Transformer No. 1 has bare conductors on the secondary which will be insulated by the liquid nitrogen bath.[2] The secondaries of Transformers 2 and 3 are insulated with Kapton, Nomex and epoxy glass tape using a system similar to that of the primary winding insulation.

The primary insulation consists of two half lapped layers of 2 mil Kapton[3] tape and one half lapped layer of 2 mil Nomex and an over wrap of butt lapped B-staged epoxy loaded glass tape.

The layer insulation between the primary and secondary windings consists of 65 layers of 2 mil thick Kapton. The space between primary and secondary windings is only 1 cm (to provide the maximum possible coupling between primary and secondary windings for maximum energy transfer from primary to secondary), which is not enough for partial discharge free multilayer insulation in liquid nitrogen.[4] In order to limit the energy dissipated during partial discharges (therefore, limiting the insulation degradation) the Kapton sheet thickness was limited to 2 mils.[4,5] Furthermore, any multilayer insulation which will be partial discharge free will not only require much more space (260 mils for 100 kV)[4] than is available for insulation, but will also be too mushy and will be structurally unacceptable. The useful life of this insulation is estimated[4] to be about 25,000 cycles which is five times the specified life of the device. To safeguard against creepage, the Kapton is extended 10 cm past the winding on each end. This provides a creepage path in excess of 20 cm in liquid nitrogen for a peak voltage of 100 kV.

TRANSFORMER LEADS

The leads of the LANL transformer operate at high voltage and connect the liquid nitrogen temperature windings to the room temperature bus conductors. Environmental and high voltage considerations provide the major design constraints: no condensation on the leads at a humidity condition of 1/2 degree Centigrade dew point depression and a low clearance above the dewar lid. Because of the low cost of liquid nitrogen and because uncooled leads have the smallest room temperature heat absorption, uncooled leads were selected. The lead current density was selected, not based upon ohmic heating considerations as is usual, but upon system resistance and adiabatic temperature rise during a current pulse.

The warm end heat leak was computed by a finite difference type computer program that has been experimentally verified by test data acquired within the Westinghouse R&D Center and from outside laboratories. The program accurately accounts for temperature dependent material properties, end conditions and the heavy electrical/thermal insulation around the leads. This heat load contributes directly to the liquid nitrogen boil-off rate and is the heat absorbed by the lead at the warm end.

The warm end heat absorption can produce a significant temperature depression at the warm end of the lead which can cause condensation and voltage breakdown of the insulation. Techniques such as thermally insulating, infrared heating, dry gas shielding, and direct and induced heating can be used to prevent warm end lead condensation. The tight geometric constraints above the dewar precluded all but active methods. The secondary leads are heated by a high temperature natural convection/radiation stove and are also dry gas shielded by using nitrogen boil-off gas inside the stove. Indirect heating allowed proper arc strike distances to be maintained at the warm end of the secondary leads.

The primary leads are fabricated from copper tubes and the tubes are adapted into a compact heat exchanger that receives heated air from a small centrifugal blower through a non-metallic tube with a suitable voltage stand-off length. Both systems are manually controlled with temperature limit controls and are designed to be fail-safe.

STRUCTURAL DESIGN

As with any high power, high voltage electrical equipment, the fundamental objectives in the transformers' structural design were to safely withstand all of the operating forces and to minimize relative motion between conductors, insulation, and structure. The major forces of concern are: the magnetic forces on all conductors, and thermal forces due to shrink fit assembly and differential thermal contraction on cooldown to 77°K.

The magnetic force distribution calculated by Los Alamos for the Transformer primary windings are shown in Figure 3. The radial force is directed outward, and the axial force is directed toward the midplane. The magnetic force distribution is similar to this in all of the windings, with the forces being slightly lower in the secondaries because of the less than unity coupling. As noted previously, significant currents do not occur simultaneously in both the primary and secondary windings. This was taken advantage by allowing hoop tension in the primary windings (which have greater relative radial depth) to support the radial forces in both windings. The resulting hoop stress distributions, along with the axial pressure distributions, are shown in Figure 4. For well-defined forces and stresses such as these, the peak stress is safely below the typical 77°K yield strength of 10-12 ksi[6] and well below the 15 ksi room temperature threshold for cyclic creep under repeated tensile loads[7] for annealed OFHC copper. However, since the yield strength is defined as the stress which produces 0.2% plastic strain, and the elastic limit is approximately one-half the yield strength in copper, some plastic strain (less than 0.2%) is expected on Transformer No. 1 during the first few cycles[8] (disregarding any hardening effect of the winding strain). The amount of interference fit to keep the primaries and secondaries in positive structural contact was set to allow for this plastic expansion during the first few cycles, along with the normal elastic and thermal expansion.

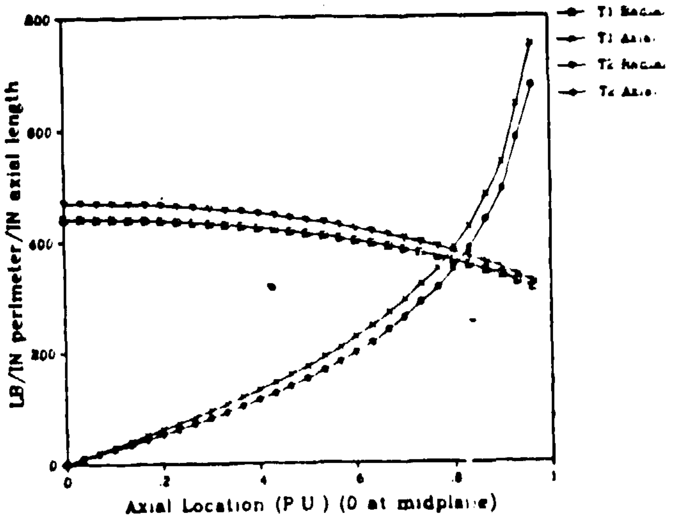

Figure 3 — Magnetic force distribution for primary windings of Transformer No. 1 (T1) and Transformer Nos. 2 & 3 (T2).

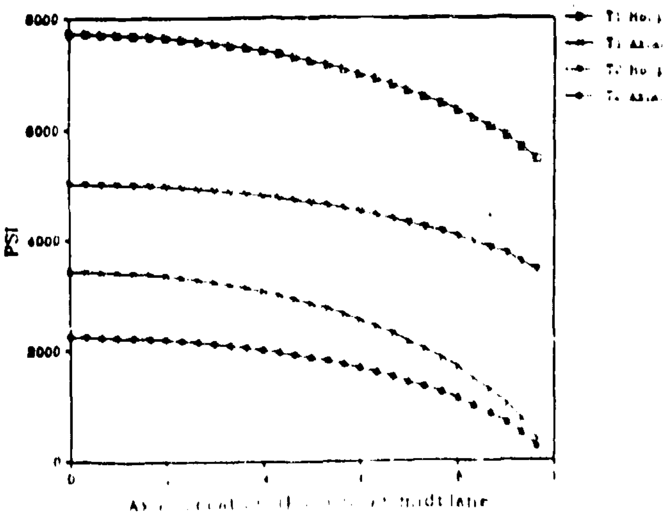

Figure 4 — Stress distribution for primary windings of Transformer No. 1 (T1) and Transformer Nos. 2 & 3 (T2).

The axial magnetic forces are also allowed to accumulate directly in the windings. In order to minimize relative axial motion between the windings, they are pre-loaded axially between G-10CR clamping plate sectors tied together with insulated aluminum studs along the outside and inside diameters of the assembled primary and secondary windings. The pre-load was set to the average axial magnetic pressure over the length of the windings, so that the overall length would not change during an operating pulse cycle.

The coil leads are the other current carrying members subject to magnetic forces. The high current secondary lead bus bars are subject to the highest forces. In this case the forces are the repulsive forces between the plus and minus leads because they are closely spaced for inductance reasons, and the current is at the megamp level. These forces are withstood by strong-backs of G-10CR along the outer faces of the bus bars, tied together with stainless steel studs along the edges of the bus bars. The significant magnetic forces on the lower current, more widely spaced, primary leads are due to the main winding magnetic fields. These forces are low enough to be reasonably accommodated by suitably sizing the tubular leads for the longest unsupported span (from the top of the transformer to the penetration through the dewar lid).

The primary thermal forces of concern are those resulting from the thermal shrink fit of the primary and secondary windings with interference, and the differential thermal contraction between the copper windings and the G-10 support cage on cooldown to 77°K. Both of these effects result in radially inward forces on the support cages inside the secondaries. The cages are made by bolting G-10 bars into flat bottom slots milled in the OD of G-10 circular plates, then machining the OD of these axial bars to the proper diameter for the respective secondary windings. This construction is well-suited for the above force pattern because all of the forces are transmitted by compression between mating flat surfaces. The resulting stresses in the support cages are well below the strength of G-10, fundamentally because the elastic modulus of G-10 is much lower than that of the copper windings.

Another thermal structural concern is the contraction of the transformer upon cooldown, relative to the ambient temperature dewar lid from which it hangs. This is accommodated in the supports by using a pin and clevis attachment at both ends of the support bars, with the pin axis tangential to the transformer circumference. In the lead bus bars, it is accommodated by orienting the thin dimension of the bars for maximum radial flexibility. In the bushing type leads it is accommodated by using an O-ring gland seal with increased gland clearance on either side of the O-ring to allow the bushing to pivot more freely at the dewar lid penetration.

SUMMARY

Design of the cryogenic transformers has posed several severe requirements. The limited insulation space between primary and secondary stretches the insulation system to its limit. The transformer lead design overcomes the major lead design constraints: high voltage operation and no condensation on the leads at a humidity condition of 1/2°C dew point depression and a low clearance above the dewar lid. The shrink fit assembly concept allows us to minimize the gap between the primary and the secondary which results in the maximum possible coupling coefficient between primary and secondary.

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